Report on the Program “Fluid-Mediated Particle Transport in Geophysical Flows” at the Kavli Institute for Theoretical Physics (KITP), UC Santa Barbara, September 23 to December 12, 2013

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Abstract

The KITP program held at UC Santa Barbara in the fall of 2013 addressed the dynamics of dispersed particulate flows in the environment. By focusing on the prototypes of Aeolian transport and turbidity currents, it aimed to establish the current state of our understanding of such two-phase flows, to identify key open questions, and to develop collaborative research strategies for addressing these questions. Here we provide a brief summary of the program outcome.

Introduction

Flows of a continuous fluid phase containing dispersed particles represent a ubiquitous phenomenon, with numerous applications in nature and technology. They can give rise to a great variety of qualitatively distinct flow regimes governed by different balances of inertial, viscous, gravitational and interparticle forces, depending on such aspects as the density ratio between particles and fluid, the nature of the particle-particle interactions, on whether the flows are dilute or concentrated, conservative or nonconservative, and Newtonian or non-Newtonian in nature, to name just a few.

Even the narrower field of geophysical particle-laden flows covers a wide variety of phenomena, ranging from Aeolian transport, dust storms and powder snow avalanches to volcanic ash plumes, sediment transport in rivers, estuaries and oceans, and dense pyroclastic and debris flows. While all of the above flows have distinctly different features, they nevertheless share a number of common aspects as well. To advance our capabilities to describe flows of this nature, the community will have to draw heavily on such fundamental research areas as the physics of suspensions and granular flows. The KITP program aimed to review the current state of our understanding of such flows, to identify the key open questions that remain, and to develop collaborative research strategies for addressing these questions via a combination of laboratory experiments, computational investigations and field observations.

The KITP program brought together a total of approximately 60 experts on turbidity currents, Aeolian flows and related topics over a three-month period, with about 20 present at any given time. The format of the program consisted of one seminar-style lecture per day, during which in-depth discussion was encouraged, which usually resulted in two-hour long sessions. Much of the remaining time was devoted to meetings of smaller groups and to individual discussions. The program concluded with a weeklong conference. In the following, we briefly summarize the current status of the field, and highlight a few of the most pressing open questions.

In order to focus the discussion, the program concentrated on the topics of turbidity currents and Aeolian transport, as representative cases for particle-laden flows involving water and air as the carrier fluids. Turbidity currents represent an important class of particulate flows. They are driven by pressure gradients resulting from spatial variations in particle loading. A beautiful and accessible introduction into the topic can be found in the book by Simpson [1]. Kneller and

Buckee [2] review turbidity currents from a geological perspective, while Meiburg and Kneller [3] focus on their fluid dynamics. Parsons et al. [4] provide a broader overview over related sediment transport processes in the ocean. Turbidity currents can be encountered in lakes as well as the ocean, where they are driven by the density difference between turbid water containing sand and/or clay, and clear ambient water. In freshwater reservoirs they contribute to the loss of storage capacity over time, and in the world's oceans they represent a key mechanism for transporting sediment from the continental shelves to the deep sea. Large turbidity currents can last for hours or even days, and they can propagate over vast distances in excess of O(1,000km), such as along the North Atlantic Mid-Ocean Channel [5]. Their interaction with the seafloor via erosion and deposition is responsible for the formation of large-scale features such as submarine sediment waves, dunes and canyons. Over geological time scales, the deposits from turbidity currents ('turbidites') can reach enormous scales of up to $O(10^6\ km^3)$, such as for example the Bengal Fan [6]. Under certain ambient conditions, the organic matter contained in the sediment may form hydrocarbons, so that sedimentary rock from turbidity current deposits plays an important role in oil and gas exploration [7]. From an engineering point of view, turbidity currents pose a significant hazard to submarine oil pipelines, well heads and telecommunication cables, both due to their impact force, as well as due to their potential for scour [8]. Turbidity currents are inherently multiscale in nature, as their large-scale evolution is closely tied to the microscale mechanisms of particle-particle interactions, erosion, resuspension, and entrainment [9].

The transport of particulate such as sand and dust by winds on Earth is responsible for the extent of desert regions, the features contained within them, and the impact that they have on the regions that surround them. This is also true of particulate transport on other bodies in the solar system with atmospheres, such as Mars and Titan. Aeolian flows are typically so dilute that collisions between particles above the bed are rare and the dominant interactions are the drag between the wind and the particles saltating (jumping) above the bed and collisions between the particles of the flow and those of the bed [10-13]. Other issues are the suspension of particles by turbulent velocity fluctuations, the influence of the particles on the turbulence, and interactions between particles in the flow and with the bed. The interest is in predicting the relation between the strength of the wind and the total rate of particle transport in natural circumstances, and in understanding how intermediate and large-scale features such as ripples and dunes develop and propagate. A characterization of sand transport is necessary to combat desertification caused by drought, overgrazing, and poor agricultural practices [14,15]. Knowledge of the mechanisms that underlie the formation of ripples and dunes allows for greater insight into the geological record and an understanding of wind directions and strengths on distant bodies. The science of Aeolian transport was initiated by Bagnold [10] and has been revitalized by a resurgence of interest in granular physics [16-19]. The state of research on sand transport and the evolution of bed forms at the start of the program is well characterized by the reviews of Kok, et al. [20] and Charru, et al. [21].

Away from the bed, turbidity currents and Aeolian transport represent dilute systems of particles in turbulent flows of water and air, respectively, whose dynamics are fairly well understood, as long as the influence of particle-particle interactions is negligible. In this region, turbidity currents and related sediment transport processes can be modeled reasonably accurately based on the Navier-Stokes equations in their Boussinesq approximation, augmented by a convection-diffusion equation for the sediment concentration field [22-25]. Such simulations can provide information on the propagation velocity of turbidity currents, on their mixing and dissipative behavior and their ability to entrain ambient water [26,27], and on their interaction with complex seafloor topography [28]. Discrete particle simulations play an important role in the modeling of Aeolian transport. They have the capacity to reproduce the velocity and concentration profiles of both steady flows over uniform beds [12,29-31] and developing flows in transitions between rigid and particle beds [32,33]. Such numerical simulations have recently been used as the bases for inferring scalings for transport in steady flows [32,34].

In the highly concentrated near-bed regions of flows of particles and water, the challenges of modeling turbidity currents and related sediment transport processes become much more complex. Here the particle volume fractions can be sufficiently high for particle-particle interactions to become dominant, resulting in such phenomena as hindered settling [35] and strongly non-Newtonian rheology [36,37]. We currently do not have a consistent, closed system of equations and boundary conditions to describe the dynamics of such highly concentrated particulate flows, or to capture the dynamic interplay between the current and the sediment bed via erosion and deposition. As a case in point, advances in the fundamental understanding of erosion following the early pioneering work of Shields [38] have been somewhat limited [39,40]. Some progress in this area is beginning to be made, at least for those systems in which inertia dominates the particle interactions. For such systems, two-phase flow theories have been phrased that incorporate the interaction between particles and between the particles and the fluid [41-43]. The predictions of such theories are now being tested against experiments [44,45]. Further progress in the field will require substantially deeper insights into the dynamics of dense suspensions, for example with regard to turbulence modification by suspended particles [46], effective settling rates in turbulent flows [47-49], sedimentation of cohesive vs. non-cohesive particulates, instabilities in sedimentation processes resulting from particle/particle interactions [50] and other issues.

Aeolian flow close to the bed is a somewhat simpler system. Collisions above the bed, which may occur for strong enough winds, can be described using methods from the kinetic theory of gases. Because of the great difference in the mass density of the particles relative to that of the air, collisions of particles with the bed (the splash) are not influenced by the wind. The measured mass and momentum transfers in them [51-55], can be employed to derive continuum boundary conditions for the mass pick-up and momentum exchanges at the bed [12]. These features make Aeolian transport a model system in that two-phase continuum equations and boundary conditions can be formulated and solved, at least for steady, uniform flows [56,57].

Current Challenges in Particle-laden Flows

Several of the key challenges we need to overcome in order to advance our modeling capabilities for particulate flows are common to Aeolian and aquatic transport processes. Among these are such issues as the modulation of turbulence by suspended particles, the modification of effective particle settling velocities by turbulence, the erosion of particles from the sediment bed as a result of turbulent flow stresses and particulate impact, and the evolution of bedforms via flow-sediment bed interaction.

From a larger perspective, a key long-term challenge identified during the KITP program is the formulation of theoretical and computational frameworks for modeling highly concentrated particulate flows in air and water, as well as their coupling with the mobile bed. Progress in this regard will have to rely heavily on the close collaboration between theorists and computational modelers on one hand, and laboratory and field researchers on the other.

The power of modern computational schemes was made clear during the Kavli program, as were their present limitations. It is clear that direct numerical simulations and/or large eddy simulations involving a discrete particle phase have matured to a point where they hold great potential to assist in the development of two-phase continuum models. In addition, computational approaches that resolve individual particles in realistic turbulent shear flows have been developed [58-61], based on immersed boundary and Lagrange multiplier techniques and related methods. Such simulations, in conjunction with experimental investigations, have already provided substantial new insight into such topics as particle settling in turbulence. However, because of the length scales involved in typical environmental and geophysical flows, these will not be amenable to fully resolved simulations anytime soon. Consequently two-phase continuum models involving turbulence models may provide the best hope in the short term for describing fluid-particulate flows at such large length scales. However, the development of such models will require empirical closures that will have to be informed by laboratory experiments and field observations.

Experimental and field techniques for Aeolian sand transport

Laboratory techniques:

Thanks to the improvement of laser based methods (e.g., Laser Doppler [62]) and imaging techniques (e.g., particle image velocimetry (PIV) and particle tracking velocimetry (PTV) [12], and time resolved tomographic/holographic PIV [63]), it is now possible to get accurate descriptions of the saltation cloud. In particular, recent wind-tunnel experiments by Rasmussen and Sørensen [62] and Creyssels et al. [12] provide a rather good characterization of Aeolian transport in terms of particle velocity and concentration within the saltation layer.

These techniques have, however, some limitations. First, they are not adequate to perform accurate measurements in the near-bed region where most of the transport occurs because of the high concentration. There is therefore a crucial need to develop new experimental techniques for better documenting this region. Second, these techniques are unable to provide direct information on the particle trajectories such as the length and height. Experimental approaches aiming at characterizing the particle trajectories use either stroboscopic methods [64] or high-speed imaging [53,65]. Theses approaches are however subject to strong operational requirements (low particle concentration, high spatial resolution, large observation windows…) which restrict their range of applications. There exists a simple alternative method to get the distribution of the trajectory length using horizontal segmented traps [13].

Another experimental challenge concerns the measurement of the air velocity and fluctuations within the transport layer. Classical probes (such as Pitot tubes or hot wires) cannot be employed because the intense particle bombardment makes them ineffective.

Field techniques:

Laser-based methods and imaging techniques are usually not suitable for grain-scale measurements in the field. For measuring sand fluxes, alternative methods are used such as vertical sand traps or more sophisticated devices based on acoustic technologies - for example, the "Saltiphone" [66]. The latter technology is currently progressing and provides an interesting alternative to the classical methods based on sand traps. In addition, their small dimension allows them to be installed in closely spaced sets and thus to provide spatially resolved measurements.

Open Questions in Aeolian Transport

Issues that must now be addressed have to do with unsteadiness and inhomogeneity in the particle flow, the way in which particle properties influence the flow, the role of the velocity fluctuations on the transport, and the identification of the mechanisms that are responsible for the development of steady bed forms.

The wind is rarely steady in natural flows and spatial relaxation to a steady state plays a key role in the development of sand dunes [67]. Consequently, it's important to describe the evolution of flows in time and space and, in particular, to understand the mechanisms responsible for this evolution. Drag, splash, and mid-air collisions are expected to play a role, but their relative importance in winds of different strengths has not yet been identified. Also, Aeolian sand transport in natural environments exhibits complicated spatio-temporal transport patterns [68], not observed in wind tunnels. These ribbons of wind-blown sand in the stream-wise direction may be related to the structure of the turbulence, but the nature of the relationship has yet to be established.

Wind-tunnel experiments indicate that the poly-dispersity of natural sand influences its transport. Existing descriptions of saltation for particles of a single size must be extended to poly-disperse flows. Sand particles are some three orders of magnitude denser than air. To understand the importance of this, systems in which the mass densities of the particles and fluid are not so different, such as snow in air [69,70], should be considered. Powder and granular snow avalanches may have their analogs in turbidity currents and collisional Aeolian flows, respectively. Turbulent fluctuations are expected to play a major role close to the threshold for the onset of saltation and at high wind speeds, when saltation is replaced by turbulent suspension. The role of turbulent fluctuations in wind tunnels and in the field must be elucidated. Also, the role of mid-air collision in sand transport at higher wind speeds [31,71] should be made clear. There is a lack of experiments to evaluate their importance and a need for further investigations in wind tunnels.

Because sand beds in Nature are rarely flat, a description of saltation transport over rippled surfaces is needed. Recent experimental and numerical investigations [72] suggest that there is a phase locking between the length of the saltation hop and the spatial modulation of the ripple. Further studies are needed to capture the relevant mechanisms that are responsible for this. The origin of the instability of a planar sand bed is now well understood [40,67,73,74], but the mechanisms responsible for the wavelength selection of steady forms are not presently known. Is such selection a linear process or is there a nonlinear mechanism at work? The mechanisms responsible for the development of steady bed forms, such as ripples and dunes, should be identified. Further investigations that couple theory and experiment are necessary.

Open Questions in Aquatic Transport

The challenges for aquatic particle-laden flows are more numerous and perhaps more difficult than those for Aeolian transport because the scales and intensities of natural turbulent shear flows range widely, as do the size, shape, density and volume concentration of the particle loading. Extreme examples in this regard are dilute turbidity currents of fine particles traversing mild inclines on the continental shelf and dense torrents of rock, mud, debris and wet snow rushing down a mountainside [4,75-77].

Fundamental progress in our ability to model aquatic particulate flows will require a deeper understanding of the collective particle-particle and particle-fluid interactions, especially for dense concentrations. Currently the rheology of such highly concentrated flows is not understood, and there is not even agreement on which variables are needed for a minimal description of the flow. Along similar lines, our current understanding of the particle exchange between the flow and the sediment bed via erosion, resuspension and deposition is still very limited. Grain sorting in movable beds [78] has received very little attention. These important, open issues will have to be investigated through carefully coordinated laboratory experiments [79], field observations [80] and direct numerical simulations.

To gain additional insight into the physical mechanisms dominating the flow-bed interaction, we must further develop current experimental techniques [39,81,82] and computational approaches [83-85] for studying the particle-fluid interactions near, at, and inside the particle bed [86]. These are the regions of densest particle concentrations, typically opaque and hence difficult to access experimentally. On the other hand, because the particle concentrations are so high, there may be ways to simplify the theoretical description of the underlying fluid dynamics. The ultimate goal lies in the formulation of continuum models for the transfer of mass, momentum, and energy between the flow and the sediment bed. These will require the derivation of effective boundary conditions at the interface that accurately capture the rates of erosion and deposition, along with the spatio-temporal evolution of the bed forms [87,88].

Conclusion

While the KITP program impressively demonstrated numerous recent advances in our understanding of particle-laden flows in nature, it also made clear that important fundamental issues remain unanswered today. Key among them is the formulation of a closed and consistent theoretical framework for describing the dynamics of such flows in the highly concentrated regime, and their interactions with the sediment bed. Progress in this regard will necessitate close collaborations between laboratory researchers, computational fluid dynamicists, theoreticians, and scientists working in the field. Importantly, we will need to develop a better understanding of how field-scale phenomena are related to laboratory observations, i.e., how geophysical fluid-particle flows scale. This will require field measurements that are informed by theory, along with field tests of theoretical predictions. A corresponding challenge exists in the theoretical/computational community, where we need to develop strategies for upscaling the insight gained from grain-resolving, direct numerical simulations to geophysical length scales.

The KITP program served to build a cooperative venture between computational, experimental, and observational scientists, and to launch novel research collaborations directed towards advancing the field of particle-laden fluid flows in Nature. At the same time, it represents only a first - albeit substantial - step. To maintain the momentum gained during the KITP program, we hope that a similar activity at the Max Planck Institute for Complex Systems, Dresden, Germany, in the spring of 2016 will consolidate and further extend this cooperative culture. In order to create the same atmosphere of open and free discussion that was characteristic of the Kavli program, the Dresden activity will involve a core of the Kavli participants, but we encourage others to attend as well. Additional information is provided at http://www.mpipks-dresden.mpg.de.

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